Ventilation techniques in the 19^{th} century: learning from the past

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Abstract

Throughout building history, various natural low pressure techniques were developed and used to improve the indoor air quality and temperature in buildings. In the 19th century, innovative heat and wind induced low pressure systems were introduced in public buildings and dwellings. Due to the further development of mechanical ventilation systems from the 20^{th} century onwards, knowledge concerning these low pressure systems was lost.

As the reduction of energy consumption of historic buildings becomes very important, the air shafts of the systems present in 19th century buildings create a unique opportunity to establish an energy efficient renovation or restoration, with maximal respect for the former technology.

The research presented in this paper aims to improve the existing knowledge on the evolution of ventilation techniques in buildings and to stimulate renovation interventions respecting the historical character of these techniques.

Based on an extended literature study, an overview of important evolutions in ventilation including the design hypotheses and problems is therefore presented. The different ventilation methods developed in the 19th century are discussed in technical detail, highlighting the opportunities and constraints when reused in renovations.
Keywords: ventilation and heating, low pressure ventilation system, wind and heat induced, historical analysis, technical understanding, renovation techniques.

1 Introduction

After several epidemic outbreaks in cities in the beginning of the 19^{th} century, the importance of a hygienic environment was finally recognized. The

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hygienists' movement stimulated the construction of sewers, the development of efficient water supplies, but also an expanded attention for the health, the hygiene and the wellbeing of the users of buildings. Special techniques found their way into the world of construction, as thought was given to the entrance of natural lighting into public buildings, to heating systems and to ventilation systems. Adequate ventilation was recognized as a key element in a hygienic environment. For example in schools, the minimum requirements on ventilation rates per pupil were studied, in order to enhance the students' study performance and quality of life, as stated by Narjoux [1].

Although the development of heating and ventilation techniques has influenced the architecture and structure of 19th century buildings and its importance is recognized by building historians, little is known by architects and engineers about the used techniques and their constraints. Heating and ventilation techniques in the 18th and the beginning of the 19th century are subject of recent studies by Gallo [2], but knowledge on the 19th century ventilation systems practical for engineers and architects is still lacking.

In this paper, the development of ventilation techniques in the 19th century is presented. The survey focuses on the different ventilation strategies and the hypotheses that support the design. The problems due to missing knowledge and incorrect hypotheses that engineers encountered will be highlighted, and how these elements can be useful in the renovation of a 19th century building with a ventilation system.

Ventilation in a historical context can be described as the deliberate introduction of fresh air and extraction of foul air in an enclosed space, with main goal to remove and dilute dangerous gasses and to regulate the indoor temperature.

Natural ventilation uses differences in air pressure to realise airflows. These pressure differences come from temperature differences (stack driven flow), and wind pressure (wind driven flow). As natural ventilation depends on climatologic circumstances, the actual performance is always an uncertainty. To ensure a sufficient air change rate in a building, two main artificial ventilation methods can be used: mechanical ventilation, using fans and ventilators, and heat and wind induced low pressure ventilation systems – or forced ventilation by heating and wind – using f.e. coils or wind cowls to induce airflows.

For this paper, the history and evolution of ventilation techniques were studied based on a literature study of 19th century manuals and treatises concerning ventilation. The evolution of ventilation techniques and knowledge transfer was analysed in an international perspective. Manuals written by architects and engineers, physicists and chemists served as an important source to track down different key events, players and buildings.

As the evolution of ventilation strategies in time is very closely related to the evolution in heating systems, the research by Gallo [4, 5] and Gresset [3] on the evolution of heating systems in France made it possible to track important sources.

Research has shown that the development of ventilation techniques happened on an international level. Sources from the USA, England, and France refer and quote each other. Important sources are the Englishmen Tredgold [6] and Reid [7], the Frenchmen Péclet [8], Morin [9, 10], Bosq [11] and Cloquet [12], the Belgian Uytterhoeven [13, 14] and the American authors Wyman [15], Billings [16], Fuller [17], Snow [18] and Hubbard [19].

2 19th century ventilation systems

In this chapter, the different ventilation systems used in 19th century buildings are discussed, the ventilation rates and calculation methods to dimension them. The opportunities for the reuse of the systems for renovation are illustrated.

2.1 Dimensioning ventilation systems

2.1.1 Ventilation volumes per person

In the 19th century, ventilation techniques were internationally studied, and several manuals and treatises concerning ventilation (and heating) were published. In France, the United Kingdom, Germany and the U.S.A., simultaneous studies were made, referring to research done in other countries. Engineers and architects, but also hygienists, physicians and chemists, were concerned with air renewal in buildings, to ensure a hygienic environment.

While the first group was mainly focused on the designing rules and the development and performance of different systems, the second group mostly investigated the ventilation rate which was needed in different settings, the constraints and criteria.

From the beginning of the 19th century ventilation becomes an important element in the manuals and treatises. The main issue was the volume of fresh air needed per person. As this was seen as a subjective matter based on observations, physicians and engineers made different hypotheses that were used to dimension the ventilation system.

In 1824, Thomas Tredgold [6], an English engineer, assumed that per person only 4 ft^3/minute or 6,8m^3/h of fresh air was needed. Based on this number, he developed a series of formulas and rules, which were easy to use and therefore very popular amongst engineers and architects. They were still copied and used by other authors 50 years later, such as the engineer Box [20]. Even in 1893, as Billings [16] states, these calculation rules were still in use by some engineers, although this value was less than one tenth of the amount of fresh air required in that period.

Tredgold – but also the French physician Eugène Péclet [8], who stimulated the dissemination of knowledge on heating and ventilation in France – made several errors in his calculations. He assumed that all air entering a room is provided by the ventilation system, without taking into account cracks and openings, and that the foul air is entirely extracted from a space, without mixing with the air in the room.

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Meanwhile in France, the focus regarding ventilation was mainly on the ventilation system in hospitals, to create a healthy and sanitarian environment. As little was known regarding their performance, forced ventilation using the different heat carriers, namely steam, water and air, and mechanical ventilation were implemented in public buildings to assess their function experimentally. As each strategy had opponents, General Arthur Morin [9] decided that when constructing the Lariboisère Hospital, both forced ventilation by heating and mechanical ventilation should be implemented to compare their results. The outcome was inconclusive, and depended on the priorities of the assessor. Morin for example preferred the central heating and ventilation system over the mechanical system and hot water as heat carrier over steam due to its lower construction and maintenance costs, while others preferred mechanical ventilation for its reliability in all seasons.

In 1857, an important breakthrough was realized by Roscoe and Professor von Pettenkofer [21], who published a paper on the chemical relations of ventilation. In this paper, the researchers tried to answer two important questions regarding ventilation, namely when does a closed inhabited atmosphere become unhealthy and how much ventilation is effected by infiltration. They found that infiltration was a larger share than assumed, but that extra introduction of fresh air is essential. Their biggest contribution is the introduction of the carbonic acid test as a measure for the amount of ventilation actually going on. For the first time, the volume of air consumed per person in different activity states could be measured. An increase in the volume of fresh air per person used to dimension the ventilation systems can immediately be noticed. In Table 1, an overview of different hypotheses in the 19^{th} century is given. The dark line represents the introduction of the carbonic acid test.

Table 1: Ventilation volumes per person provided in the 19^{th} century.

Year	**Author/ Type**	**Country**	**Volume of fresh air per hour per person (m³/h)**			
			general	hospitals	Elementary Schools	army barracks
1824	Tredgold, T.	UK	6,8			
1838	Arnott	UK	3,6- 4,8			
1846	Law	France		60		
1860	Morin, A.	France		60-100	12	30 – 60
1860	Law	UK				34
1864	Parkes	UK				57
1875	Bosq, E.	France		75-150	15	30-55
1874	Law	Belgium			14,4	
1891	Box, T.	U.S.A.	*7,1*	57-114		
1898	Dumas & Leblanc	France	*6-7*			
1898	Sanitarians	UK, France, U.S.A.	75			
1898	Cloquet, L.	France, Belgium	15-25			

Although as stated above and illustrated in italic in Table 1 some engineers kept using insufficient ventilation rates to dimension the ventilation system, the different countries created laws to ensure minimum ventilation in public buildings from 1860 onwards.

The average air volume per person remained a point of discussion between engineers and sanitarians as Cloquet [12] stated in 1898. The 15 to 25 m³/h he suggested, was a realistic average, which approaches a moderate indoor air quality (IDA 3, 22–36 m³/h per person) according modern ventilation standards.

In the beginning of the 19th century heating and ventilation was still an experimental science, and the design and calculation of systems were made by autodidacts. From 1860 on engineers were trained it the matter. In France, due to lecturers at the 'Ecole Centrale' as Péclet and Trélat, and Belgium the mechanisms and theory behind central heating and forced ventilation by heating were widely spread, and by the end of the 19th century, these systems were widely used in public buildings. Research on mechanical ventilation does however not stop, and from the beginning of the 20th century on, mechanical ventilation gains in importance and slowly repulsed heat and wind induced low pressure ventilation systems. For example in the treatise by Fuller [17] from 1914, only the calculation of mechanical ventilation is included.

2.1.2 Dimensioning the air extraction shafts

To dimension the inlet of the foul air in a room, the different air channels and the chimney, the air velocities in every element were empirically determined through acoustic constraints.

According to Cloquet [12], when calculating the diameters of the air flue, the air velocity of the extracted air should lie between 1m/s and 1,5m/s.

Bosq [11] states that the air velocity of the foul air at the inlet in the room should not exceed 0,7 m/s. The head collector duct should be calculated at 1,2 m/s; the secondary ducts at 1,3m/s. In the air flue, the velocity of the air should be around 1,9 m/s. To dimension each element, the volume of air required per person should be multiplied by the number of people present in the room, and divided by the air velocity in the element, which gives the area of the shaft or inlet.

2.2 Ventilation systems of the 19th century in technical detail

In the previous part, we discussed the evolution of different ideas, hypotheses and experiments on ventilation. Ventilation evolved from empirically based knowledge to more theoretical insight from 1857 on, due to Dr. Pettenkofer and his carbon acid test. This led to the development and optimization of the different ventilation strategies. The following chapter presents the different ventilation systems used from mid 19th century till the beginning of the 20th century. The use of every system depends on several constraints including environment, atmospheric variations, wind flows and the building constraints: the organisation of the different spaces, their function and the amount of ventilation required.

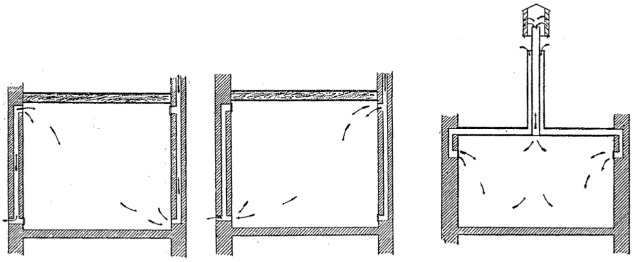
All systems presented, were to be included at design stage in the building. The impact of the ventilation and heating system on the structure and layout of a building was huge, as ducts, heating devices or fans had to be incorporated in the carrying structure of the building. Even in the 19th century, architects and engineers strived to a more holistic design approach, including concept, construction and techniques from the start of the design process, an idea that is now more actual than ever.

2.2.1 Natural ventilation

Natural ventilation uses differences in air pressure to realise airflows. These pressure differences come from temperature differences and wind pressure. At least one inlet and one outlet per room is needed to induce an airflow.

In the 19th century, in most dwellings, ventilation was realized by the opening and closing of windows, together with infiltration through cracks and openings. By opening windows, a large ventilation rate could be realized, as long as a temperature difference between indoor and outdoor existed, or wind was blowing.

In buildings with a bigger occupancy, more active ventilation was needed. To maximize the effect of the natural forces, different setups where developed, as illustrated by Figure 1. Dr. Bohn, an Austrian scientist, tried to maximize the stack effect by incorporating ventilation ducts in the walls to introduce and extract air (Figure 1(a) and (b)). Both ducts have openings at the ceiling and the floor, that can be closed, but one duct is as high as the ventilated room and the other one is in connection with the roof. When the internal air is warmer than the external air, the outdoor air will enter the room at ceiling height, and descend, as foul air is extracted at floor height. In summer time, the fresh air is supplied at ceiling height by the duct in connection to the roof, and foul air is extracted at floor height. In the Mac-Kinnel system (Figure 1(c)), an air flue is combined with a roof discharge element, to optimize the wind effect.



(a) (b) (c)

Figure 1: (a) Bohn system winter; (b) Bohn system summer; (c) Mac-Kinnel system – Cloquet [12].

2.2.2 Mechanical ventilation

Natural ventilation depends on climatologic circumstances. When the temperature difference is too small and wind is lacking, no sufficient ventilation can be realized. In a mechanical ventilation strategy, fans and ventilators are introduced to ensure a sufficient air flow.

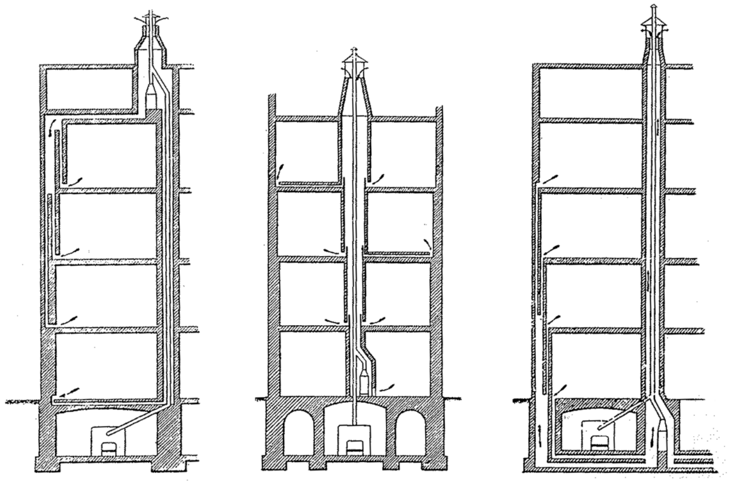
In the 19th century, both aspiration and insufflation apparatus were developed. The first extracted the used air, so that fresh air was sucked into the room; the second blew fresh air in a room which created an overpressure. The insufflation method allowed to control and to handle the incoming air.

Mechanical ventilation had as big advantage that no chimneys had to be constructed, which decreased the construction cost. The installation was straight forward, and the risk of fire in a building reduced significantly.

2.2.3 Heat induced low pressure ventilation

The air flow in a building can also be stimulated be increasing the temperature difference between the outdoor temperature and the foul air to extract. In the 19th century, innovative heat and wind induced low pressure systems were introduced into public buildings and dwellings. The low pressure differences induced air flows. In winter time, the natural temperature difference between the interior and exterior air was sufficient to supply fresh air and to extract the used air from the rooms, but in summer time this was not the case. Heating elements were introduced into the duct system to induce an adequate draught in the air channels. Three types of forced ventilation by heating were developed, differing in the position of the heating device in the air flow, with each its advantages and disadvantages.

In Figure 2, the three setups are illustrated: top ventilation, level ventilation and bottom ventilation.



(a) (b) (c)

Figure 2: Heat induced low pressure systems: (a) top ventilation; (b) level ventilation; (c) bottom ventilation – Cloquet [12].

Top ventilation

In this setup, in winter time, fresh air was heated by a heating device in the lower parts of a building, and then transported by ducts to the different rooms. The foul air was evacuated from each room by a vertical channel incorporated in the walls, and enlarged with each air flow added. In the attic, the chimney of the heating device in the basement and the extraction ducts joined together. The foul air was extra heated by the smoke extraction ducts, and left the building through a roof extraction element.

In summer time, fresh air entered the room without being heated. As the indoor air temperature was lower than the outdoor air temperature, an extra coil in the attic, heated the foul air so that the air could be extracted.

In this system the stack effect was not optimally used. It had as biggest disadvantage that in the upper levels of the buildings, the ducts were at their largest, while the walls from constructive point of view could be the narrowest.

Level ventilation

In the heat induced level ventilation setup, a central chimney containing the smoke extraction duct of a heating device in the basement will extract the foul air. Every room is directly connected to this air flue, with horizontal ducts. In this system, the vertical extraction ducts are eliminated, which facilitates the wall construction. Horizontal ducts incorporated in the floors were nevertheless not very easy. The different spaces to be ventilated were ideally situated around the central chimney, so this system was not appropriate for every building design.

Bottom ventilation

In the top ventilation setup the foul air was transported in ducts to the attic, where it was heated to be extracted. In reverse, in the bottom ventilation setup the used air was transported by the air extraction channels to the basement. At each floor, the air flow in the ducts increased, and its diameter enlarged. In the cellar, the air was heated by a heating device (and the smoke it produced) and left the building through a chimney, that also incorporated the smoke extraction ducts.

Due to the larger ducts at the foundation of the building, constructive constraints must have been taken into account when using this system. The biggest advantage, however, was that the stack effect of the chimney was used to its optimum. The system performed therefore a lot better than the level or top ventilation system. It is therefore not difficult to understand why this heat induced low pressure ventilation system was mostly used in public buildings in France and Belgium, for example in elementary schools.

To create an appropriate draught, the temperature in the chimney should be around 30 to 35°C in the chimney, according to Bosq [11].

2.2.4 Hybrid systems: heat and wind induced ventilation combined with mechanical ventilation

In hospitals and theaters, the ventilation system at the end of the 19th century was often a combination of forced ventilation by heating and mechanical ventilation by insufflation. This setup allowed a good ventilation rate, combining the reliability of mechanical ventilation with the advantages of forced ventilation heating. In Figure 3, the ventilation system of a hospital in Ghent, Belgium is illustrated. Fresh air is introduced by a ventilator in ducts, where the air can be preheated, and is pulsed in the room at ceiling height. The foul air is then extracted at floor level, and is heated in the air flue by a coil.

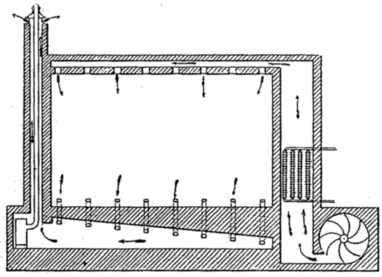


Figure 3: Ventilation system Byloque hospital, Ghent by M. Pauli – Cloquet [12].

2.3 Opportunities for reuse and incorporation of 19th century ventilation systems as a renovation strategy

In the previous parts, the different ventilation systems used in 19th century buildings are discussed, and the ventilation rates and calculation methods to dimension them. This allowed investigating how the ventilation systems were dimensioned and what constraints were taken into account.
The ventilation rates, on which the systems were dimensioned, are an important parameter while renovating or reconverting existing buildings. Once is known what ventilation is possible with the existing shafts, the engineer can assess the possibilities to incorporate them in a new ventilation system.

In Table 1, it is clear that most of the ventilation systems were designed using ventilation rates well under the modern standards, with exception of hospitals. The high ventilation rates per person provided in these buildings, are the result of the misassumption that ill people excrete more gasses than healthy persons and that therefore more ventilation was required. For old infirmaries, were the systems were mostly dimensioned to provide around $60m^3/h$ per person of fresh air, the system can be used to provide for the same occupation an excellent indoor air quality IDA1. When reconverting these buildings into f.e. offices, the ducts available in the building are likely to be well dimensioned.

But other buildings, where the system is dimensioned with low ventilation rates, also have potential. This can be illustrated with the case of elementary schools. In Belgium, in 1874, a law stipulated that in each classroom an air change rate of 2 volumes per hour had to be realized, on city level this became even 3 volumes per hour in Brussels, which meant for a standard size class room with 46 pupils around 14,4 m^3/h per pupil. When renovating these classrooms, another occupancy rate will be used. According modern Belgian standards, the maximum occupation for such a classroom will now be around 20 pupils, so that with the same system, around 30 m^3/h per pupil can be provided, which corresponds to an indoor air quality IDA 3, the minimum requirement for class rooms nowadays.

Including the existing ventilation system of a building in a renovation, is therefore possible, but every building type needs to be studied in detail. The former use of the building and the new occupancy and function after renovation will dictate the constraints of the system. Per type of building can thus be investigated what function and occupancy rate is optimal to modern ventilation standards.

3 Conclusion

This paper gives an evolution of ventilation techniques in buildings in the 19th century, to stimulate renovation interventions respecting the historical character of these techniques.

In the 19th century ventilation became an important aspect in building constructions. Ventilation evolved from empirically based knowledge to more theoretical insight from 1857 on.

This led to the development and optimization of the different ventilation strategies. The different ventilation methods developed in the 19th century are discussed in technical detail: natural ventilation, forced ventilation using heat and wind induced low pressure systems and mechanical ventilation. The opportunities for the reuse and incorporation of the 19th century ventilation systems as a renovation strategy were highlighted.

Acknowledgement

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